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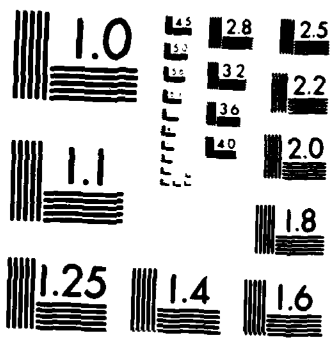
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The Man-Machine Interface

Robert U. Ayres

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Carnegie-Mellon University
The Robotics Institute

Technical Report

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Engineering and Public Policy
The Robotics Institute
Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

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Our objective was to define a composite measure of human capabilites that could also be used to measure the "skill" requirements of various manufacturing tasks. In the course of our research, however, we have come to the conclusion that most human workers (at least in the "semiskilled" categories) are not employed for their manual skills, or dexterity, but for a different purpose. Although our basic objective remains unchanged, our research focus has shifted to the emerging competition between human workers as machine process controllers in certain highly engineered environments, and the use of sensor-based, computerized systems for the

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Table of Contents

List of Figures

List of Tables

Abstract

Our basic objective was to define a composite measure of human capabilities that could also be used to measure the "skill" requirements of various manufacturing tasks. In the course of our research, however, we have come to the conclusion that most human workers (at least in the "semiskilled" categories) are not employed for their manual skills, or dexterity, but for a different purpose. Although our basic objective remains unchanged, our research focus has shifted to the emerging competition between human workers as machine process controllers in certain highly engineered environments, and the use of sensor-based, computerized systems for the same purpose. [illegible] computer applications, machines, [illegible]

1 Executive Summary

The research reported here was initiated under a grant from the Education and Training Administration of the U. S. Department of Labor (ETA) entitled, *A Methodology to Predict the Substitutability of Robots for Factory Workers, Based on a Dexterity Measure.* At the outset, our objective was to define a composite measure of human capabilites that could also be used to measure the "skill" requirements of various manufacturing tasks. This basic objective remains unchanged. In the course of the research, however, we have come to the conclusion that most human workers, at least in the "semiskilled" categories, are not employed for their manual skills, or dexterity, but for a different purpose. They essentially perform a real-time control function that involves receiving a flow of information on the "state-of-the-system" and responding effectively to that information. In this context, manual dexterity is relevant only to the extent that it reflects this information processing function.

Our research focus has shifted, therefore, to the emerging competition between human workers as machine or process controllers in certain highly engineered environments, and the use of sensor-based, computerized systems for the same purpose. Comparative advantage in these circumstances depends primarily on the nature of the information required to make control decisions. To simplify a very complex situation, machines are inherently faster, more powerful, more reliable and more accurate in repetitive operations than humans, but humans have far superior vision and taction senses, including the ability to decode and interpret sensory inputs. In particular, if the essential information is inherently available in forms easily accessible to human senses, an electronic substitute is unlikely to be cost-effective for decades to come. On the other hand, if the human worker depends on an electronic interface to present the critical information in an accessible form, e.g., via dials, readouts, or displays, it is very likely that the human can, and soon will, be eliminated from the control loop.

This insight does not immediately tell us which factory jobs will be soon replaced by automated systems, except in a few fairly obvious cases. However, it does provide an important clue: if the critical control information is provided via eyes and/or the sense of touch, it can be presumed that human information-processing and feedback capabilities are being significantly utilized, and machines will probably be at a disadvantage. Conversely, if control decisions do not require visual or tactile information, the advantage lies with machines. This implies that *if performance of a task is severely degraded when the worker is deprived of one of these two senses, the required flow of information is both directly accessible and quantitatively important. The more severe the degradation, the greater the inherent advantage of human workers over machines for the task in question. Thus, the quantitative degree of degradation as a function of sensory deprivation constitutes a measure of the relative advantage of human workers vis-à-vis machines.*

For tasks where performance is severely degraded by lack of sensory inputs, robots will not be cost effective in the near future unless the machine controller can utilize internal feedback of (non-visual, non-tactile) information. In general, this is possible only in cases where the spatial relationships between the machine and workpiece are predetermined and invariable. On the other hand, for tasks whose performance by humans is not seriously degraded by sense deprivation, robots are likely to compete effectively already or in the very near future.

Quantitative data is presented on the relative sense dependence of various task elements, on the degradation in performance that results from reducing the availability of sensory feedback, and on the relationship between tactile and visual information in various task elements.

2 The Role of Labor in Manufacturing Activities: Economic Perspective

The manufacturing sector, as distinguished from extraction, construction, or services, is devoted to the conversion of raw materials into finished and portable products ranging in size from tiny electrical components or fasteners to that of ships, and ranging in complexity from nails to supercomputers. Activities can be subdivided into several basic categories:

- Materials processing (refining, alloying, rolling, etc.)
- Parts manufacturing (cutting, forming, joining, finishing)
- Parts assembly and packaging
- Inspection
- Shipping, storage, maintenance, sales, etc.

Materials, energy, capital and labor are said to be "factors of production." As a rough generalization, factors of production are regarded as substitutable for each other, i.e., labor or energy inputs can be decreased by increasing capital inputs. (This is not true, of course, for materials actually embodied in the product.) On closer scrutiny, such substitutions are typically possible only at the margin and in a rather restricted sense.

To make this point clearer, consider the role of fixed (physical) capital, disregarding liquid working capital for the moment. Capital plant and equipment is of several distinct kinds, *viz.*,

- tools, dies, patterns
- *machine tools and fixtures*
- materials handling equipment (e.g., pallets, conveyor belts, transfer machines, pipes, pumps, forklifts, cranes, vehicles)
- containers (shelves, bins, tanks, drums)
- structures and land

Machine tools do substitute for workers insofar as they wield tools such as hammers, drills, punches, saws, milling cutters or grinding wheels, files or cutting implements similar in function to hand tools as used by human workers. Machine tools are now used almost universally in manufacturing (at least in developed countries) because they can be faster, stronger, more accurate and tireless than human workers using hand tools. Motor vehicles are used for transportation (in developed countries) for similar reasons. Containers and structures are required to store and protect materials in process, as well as sheltering tools, machines and workers from the elements. Clearly, these categories of capital are complementary; capital in one category cannot substitute for capital in another. Traditionally, the substitution of capital for labor has meant the greater employment of machine tools in place of manual tools, and motorized forms of transportation in place of non-motorized ones. But until recently, each machine has needed a human operator. In short, machines have been substituted, in the past, mainly for human arms, legs, and hands. The question implicit in the title of this report can now be made explicit: *To what extent can machines be expected to take over other functions of human workers in the near future?*

To elucidate this question, we need a better functional taxonomy of repetitive factory tasks that are directly related to fabrication or assembly of parts. For present purposes, we can ignore workers whose jobs are non-repetitive, i.e., concerned with building or machine maintenance, setup, scheduling, inventory, transportation, product design and testing, administration or sales. The major generic task categories are

- parts recognition, sorting and selection,
- machine parts transfer loading/unloading,
- tool-wielding,
- parts inspection,
- parts mating (assembly).

All of these generic tasks can be accomplished, in principle, either by machines or by human workers. The most common patterns in factories today are shown in Table 1. In custom (or small batch) manufacturing, most control tasks are and will remain largely manual simply because it is not worthwhile to mechanize any task that is not highly repetitive. The increasing use of programmable machine tools in small shops does not contradict this conclusion, it reflects the fact that NC machine tools are becoming easier to program so that microprocessors are able to control operations that can be entirely committed to memory in advance. In larger batch manufacturing, machine tool loading/unloading is gradually being taken over by robots or programmable feeders, while assembly remains largely manual though machine-assisted. Insensate robots also perform some tool-wielding operations (e.g., welders, spray painters, glue guns). In mass production situations, mechanization now extends to virtually *all* tasks except for magazine *loading, inspection and* assembly. Even these are machine assisted.

In virtually all cases, the remaining non-mechanized but repetitive factory jobs of today seem to require a significant level of sensory feedback. In fact, it is quite realistic to regard most factory workers in the semi-skilled job classifications as "operatives" (BLS terminology) or "machine controllers" to use a term that perhaps conveys better the essence of the human role in the production system.

In abstract terms, the human factory worker can be modeled as part of an information processing feedback system.[1] He (or she) receives status information from the machine, the workpiece and the environment. He processes and interprets that information, arrives at certain conclusions, and translates those conclusions either into new control settings for the machine or a new position/orientation for the workpiece. The amount of true intelligence required by the worker depends on how limited the set of possible responses is, and how precisely the criteria for choosing among them can be pre-specified. In many cases, the worker need only decide whether the last operation was successful and signal for the next operation to begin. The major

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[1]This insight was expressed at least 35 years ago by Norbert Wiener in *Cybernetics* (1948), and a number of early workers in "human factors"/ergonomics. It is reconsidered later in this report.

Table 1: Mechanization vs. Scale of Production

Task Category	Custom	Batch	Mass
parts recognition and sorting	manual	manual	not applicable (N.A.)
parts transfer	manual	transitional (e.g., belt machine)	mechanized (e.g., transfer machine)
machine loading and unloading	manual	mostly manual	mechanized (e.g., feeders)
tool-wielding including machine operation)	semi-mechanized (manual control)	mostly mechanized (NC) except for supervisors	mechanized, fixed sequence
parts inspection	manual	manual	transitional
parts mating and assembly	manual	mostly manual	transitional

difference between jobs requiring semi-skilled and skilled workers is that the former jobs involve relatively few and simple choices, each made many times, whereas the latter jobs involve a very wide range of possible choices. Intelligence is involved when the range of choice is so wide that each case is likely to be unique in some respects, requiring the worker to extrapolate or interpolate from known and understood situations. (This is the essence of a non-repetitive job, of course.)

This perspective on the status of factory automation and its future directions was articulated by James Bright (1954). An updated version of his well-known "automation ladder" is shown in Table 2. It is evident that the state-of-the-art is roughly at level 11. Advances between successive levels are not equally difficult (in fact level 9 appears technically trivial) but the tendency toward elimination of humans as semiskilled machine controllers is unmistakable.

Obviously, one of the broad, long-run objectives of automation, from a management perspective, is to reduce the need for highly skilled personnel by designing and engineering the manufacturing system in such a way as to minimize the ambiguity and uncertainty associated with the various steps in the process, and thus tha amount of intelligence and experience required of the workers. What all this means, in practice, is that most factory workers in industrialized countries are employed not for their knowledge or mental abilities, but primarily for their senses (vision, hearing and touch or "taction") and for their "eye-hand" motor

Table 2: Automation Ladder

Bright Level	Power	Initiating Control Source	Control and Feedback Signals	Machine Response	Level of Mechanization Characterization
1	Human	Human	touch,eye	NA	hand
2	"	"	" " (ear)	"	hand tool
3	Electric or gas engine	"	"	Action determined by operator	power hand tool
4	Any Prime Mover	"	" "	"	machine tool, manual control
5	" "	Built-in analog program(stops,cams)	Force,motion of machine itself	Action fixed by mach.design	machine tool,fixed cycle,single function
6	"	"	" "	"	sequence of fixed cycles,multi-function
7a	"	External analog program (e.g. puched tape)	" "	Action fixed by program	" variable cycle (remote control)
7b	Electric	External EM analog program(mag.tape)	above,converted into EM signals	"	" Numerical Control(NC)
7c	"	External EM digital program	" "	"	" "
7d	"	" " via microprocessor	" "	"	Computer Numerical Control(CNC)
8	"	" "	above,plus force feedback from workpiece/tool	above,plus feedback	above, self-actuating (stop/start)
9	"	" "	above,plus EM signals from workpiece/tool	"	above,measures characteristics of workpiece before/after perf.
10	"	" "	" "	"	above,detects(some) errors & stops
11	"	" "	" "	"	above,records perf. for later evaluation
12	"	" "	" "	Action based on feedback, limited 'menu'	Intelligent systems – Alters speed,position & direction
13	"	" "	" "	"	Dimensional inspection (accept/reject)
14	"	" "	" "	"	Alters sequence of actions(from menu)
15	"	" "	" "	Action based on feedback & wide range	Correct errors after detection
16	"	" "	" "	"	Corrects performance while operating
17	"	" "	" "	"	anticipates action required

coordination. Since these are inherent qualities, not learned ones, it is increasingly difficult for manufacturing firms to justify the locations or retention of facilities in regions, or countries, with high prevailing wage rates for unskilled labor.

The foregoing generalization seems intuitively plausible, but it is important that the Department of Labor and other agencies of government, as well as private sector planners, to address the potential for labor substitution in much greater detail. We need to estimate *what* job classifications will be affected, by what *types* of automation, and in *what* time frame. Many problems arise in attempting to answer such questions, especially in the realm of technological forecasting, and economic analysis. But even if adequate technological forecasts and economic analyses were feasible today, serious conceptual problems would remain in comparing human and robot performance for specified jobs. These conceptual difficulties arise from the fact that while machines may be able to substitute for human workers for many given tasks, they are not 'substitute workers'.[2] Robots and machine tools do some things better, e.g., faster, heavier loads more accurately, than humans, but machines perform other tasks more slowly than humans. There are some tasks that machines are currently unable to perform at all. Machines have abilites, by vitue of their construction, that are very different from those of humans. This makes direct comparison in any across-the-board sense quite difficult. To come to grips with the problem of man-machine comparison, we need to develop explicit measures of task performance for each task/scale category in Table 1. This is addressed in the next section.

To be sure, some procedures have been developed to deal with the problem systematically. To begin with, many manufacturing jobs have been analyzed in terms of 'elementary motions' and, in principle, any manual task can be decomposed in this way. Compendia of tables are distributed by the Maynard Foundation, giving average times required for each elementary motion (Maynard et al. 1948; Antis et al. 1979). By extension, it is possible to estimate the labor time required for any well-specified task, assuming workers are equipped with normal sensory capabilities.

In a comparable manner, it is possible to decompose all tasks do-able by a robot into a set of elementary motions. Each elementary motion for the robot corresponds to an instruction in the robot control language. Again, it is possible to determine actual and average times for specific robots. Some of this data has already been accumulated by a group at Purdue University (Paul and Nof 1979; Nof and Lechtman 1982).

But, as noted, robots and humans are not directly comparable in time/motion terms because they have different sensory and information processing capabilities. Specifically, robots can be stronger, faster, or more

[2]The original meaning of "robot" (from the Czech word *robotnik*) was a substitute worker, but today's industrial robots are, at least, a crude mechanical substitute for one arm and two stiff fingers.

precise, and they are certainly tireless. But they do not see or feel (unless fitted with a special vision or taction system) and lacking senses, they must repeat a task from internal feedback signals, if any, and stored memory. Humans, on the other hand, use *external* sense-based feedback to control their motions. In consequence, humans almost never perform a task exactly the same way twice. These differences are fundamental: They explain, in part, why direct comparison between the capabilities of human and robot workers is extremely difficult.

3 Objective Functions for Repetitive Factory Tasks

The task classification given in Table 1 yields some further insights if we ask: what is the appropriate *objective function* for each task category? An objective function is an explicit combination of variables that is maximized (or minimized) as a whole when the task is accomplished in the best possible way. In principle, maximizing the function is equivalent to achieving the objective of the task. For the economy as a whole, the conventional choice of objective function is something like the discounted present value of future GNP, while for a firm the conventional choice might be the discounted present value of future profits. However, when a firm's activities are further disaggregated into distinct functions such as manufacturing, sales, and finance, the choices are often somewhat less obvious.

For manufacturing as a whole, the objective would seem to be to maximize output per unit cost -- again, in a present-value sense. But what is involved in maximizing output? One factor common to all repetitive tasks is speed or rate of processing, i.e., the number of parts "processed" per hour. The term processing, used above, can obviously refer to parts recognition, selection, transfer, machine loading/unloading, cutting, inspection or assembly. In the case of machine tools, the rate of machining, or metal removal, is directly proportional to the rate of energy expended by the tool on the workpiece. The rate of energy use is equal to the power consumption.

But maximizing processing speed alone does not necessarily maximize output per unit cost because machining (and assembly) operations are also constrained by precision requirements for the positioning and orientation of the part with respect to the tool (or conversely). One can almost increase processing speed by sacrificing precision, and vice versa. This tradeoff is discussed in more detail later. Allowing for the possibility of tradoffs like this, a better statement of the objective function for metalworking operations would be to jointly maximize operating rate (or in some cases, power delivered to the workhead) and precision together. Thus, for operations requiring speed and precision of motion along a line, a generic objective function (OF) might be

$$\max \frac{\text{rate of processing}}{\text{tolerance x cost per unit}} \quad \text{in} \quad \frac{\text{units per second}}{\text{cm x \$}}$$

For operations requiring the application of force or energy at a precise point on a line, for example, a spot welder or drill, an appropriate OF seems to be

$$\max \frac{\text{power delivered}}{\text{tolerance x cost per unit}} \quad \text{in} \quad \frac{\text{watts or joules per sec.}}{\text{cm x \$}}$$

If the machine operation requires precision of location in two or three dimensions, the denominator presumably takes on units of area (cm^2) or volume (cm^3). In fact, higher dimensionalities may also occur. For the present, however, we restrict ourselves to the simplest case where precision need only be considered with respect to a single linear dimension.

Note that the generic objective functions suggested by the above arguments apply to the *task* irrespective of the degree of mechanization or machine assistance. It is the task itself that calls for a joint maximization of speed or power and precision. The power and precision required, in turn, depend on the size of the workpiece, the hardness of the material, and the part design (which depends on its intended function in the final product). The optimum degree of mechanization, including the choice between a human-controlled sensate machine tool or a computer-controlled machine tool, or a computer-controlled sensate machine tool over a robot, depends on the cost-minimizing combination for each case. As noted above, this is a function of the product design and scale of production. To summarize, plausible generic objective functions for the various task categories are shown in Table 3.

Table 3: Objective Functions for Repetitive Factory Tasks

Task Category	**Objective Function (OF)**
I parts transfer; machine unloading	$\frac{\text{rate (in units per sec)}}{\text{cost per unit (\$)}}$
II parts recognition, sorting, selection, machine trading, parts mating, inspection	$\frac{\text{rate (in units per sec)}}{\text{tolerance (cm) x cost per unit (\$)}}$
III tool wielding	$\frac{\text{power delivered (in watts)}}{\text{tolerance (cm) x cost per unit (\$)}}$

4 Speed Versus Precision

Given that the generic objective functions for repetitive task categories shown in Table 3 are realistic (in a factory context), it is appropriate to consider again the role of sensory information processing in accomplishing the tasks in group II and group III. Because the cybernetic control system of human workers is highly dependent on external sensory information, it follows that the time required to accomplish any task element, such as an arm movement, depends on the degree of precision that is needed. There is a direct tradeoff between error-rates and speed. In fact, experimental psychomotor research carried out in the early 1950's has suggested the following formula to explain the observed relationships between time, task difficulty, as measured by the number of alternatives to be considered, and required precision. Let T refer to elapsed time, then

$$T = K_p + K_m + C_d H_t + C_m \log(2A/t) \tag{1}$$

where K_p is the minimum delay time associated with sensory perception, K_m is the minimum delay time associated with motion, C_d is the information-processing coefficient in seconds per bit, H_t is the amount of information to be processed in bits, C_m is the information-handling coefficient associated with motion in seconds per bit, while $\log(2A/t)$ is the amount of information required to move a distance A with tolerance t (Hick 1952; Fitts 1954; Salvendy and Knight 1982). Both A and t are measured in units of distance (inches or centimeters). The parameter K_p depends on the mode of perception; for vision it ranges from 0.15 to 0.225 sec., while for tactile perception it ranges from 0.115 to 0.19 sec. The parameter K_m is approximately 0.30 sec. for hand movements. The information processing term $C_d H_t$ is important in cases where the worker must make choices, as in distributing N different kinds of parts among an equal number of bins. In this particular case, H_t would be given by logN. The coefficient C_d is approximately 0.22 sec.

For a task where the worker has no decisions to make, only the time vs. precision relationship need be considered. For a human worker, the maximum rate of output information-processing is $1/C_d$ or 2/0.22 bits/sec. Hand movements occur in two stages. First, there is a gross ballistic motion which is vision-controlled to about 7% accuracy. This is followed by a series of successive corrections, each of which takes 0.30 sec. and reduces the error by a further factor of 93%. Thus, the error reduction factor for each iteration is 14. It can be seen quite easily that C_d must be equal to, or greater than, 0.3/log14 or 0.065 sec. Ann approximate value for practical estimates is 0.1 sec.

Since all manufacturing operations consist of decisions and motions, processing speed and precision evidently tend to interfere with each other, in general. This is not really a problem at low speeds and low degrees of precision. But it is a commonplace observation that any high precision operation, such as lens-grinding, tends to be rather slow because the workpiece must be repeatedly measured and compared with the desired specifications. The procedure consists of a sequence of machine operations followed by tests and tool adjustments. As the workpiece approaches its final dimensions, the measurements become more exacting, the adjustments become finer, and the periods of machine operation, e.g., cutting or grinding, become briefer. In an extreme case, such as the grinding of the famous 100 inch reflecting telescope for the Mount Palomar observatory, most of the aggregate processing time is actually spent in measurement and adjustment, which are forms of information processing.

In a typical plant that manufactures larger numbers of less exotic products, the manufacturing process is broken up into successive stages, beginning with rough operations that can be carried out at high speed using powerful machines, and concluding with finishing operations that are slower but more precise. The higher the standard of precision that the final product must meet, the more inspection is required between successive stages, and the slower and more costly the process will be. In fact, a standard rule-of-thumb in industrial engineering practice is represented by Figure 1.

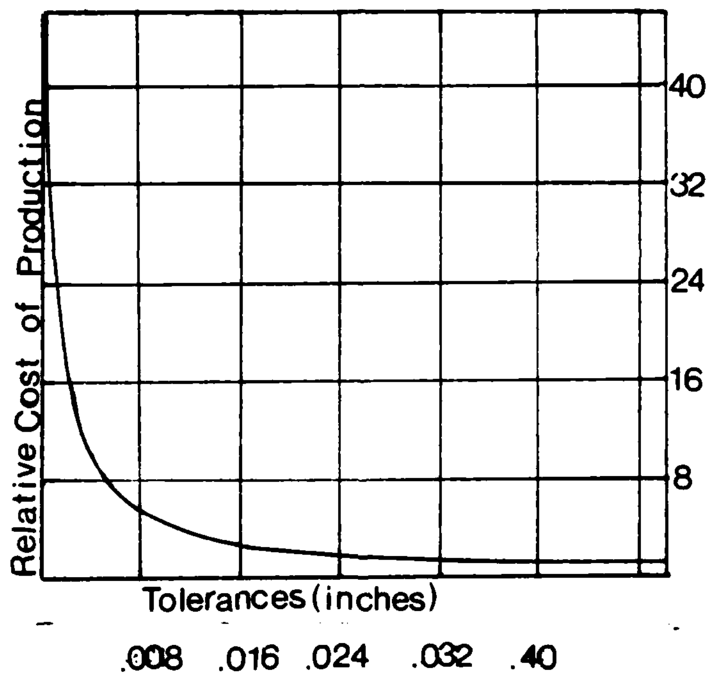

Figure 1: Typical relationship between tolerance of a part and cost of machining

Figure 1 implies that the achievement of higher precision, i.e., smaller tolerances, requires either more costly capital equipment or more labor time, or both. The capital equipment needed to manufacture high precision products is more costly because it, too, most be made to higher standards of precision (Figure 1, again). Ultimately, higher precision manufacturing requires more *labor* time, i.e., information-processing time, whether that time is used directly or embodied in complex machines. Thus, the inverse relation between process time and tolerance that was derived for elementary motions and the tasks components above (equation 1), is also applicable to factory operations in general.

As noted earlier, most human workers classed as "operatives" in factories today are employed not because of their strength and speed (nor for their intellectual or linguistic abilites), but specifically to utilize their visual and tactile information processing and motor coordination abilities. Humans acquire information about the state of the system being controlled via the senses of vision, hearing and touch, and learn to correctly interpret and respond to such information in a particular context. The essential validity of this statement can be confirmed by comparing human workers' capabilities with machine capabilities with respect to the variables in each of the three different objective functions (OF's) in Table 3. Consider the three variables separately:

Rate (or speed): If identification is not involved, and weight and/or precision of location are not constraining factors, humans can feed or transfer small parts, one by one, at rates of the order of 1 per sec. Transfer machine magazine feeders and rotary bowl feeders can achieve consistently higher operating rates than humans for parts of a given size. But the speed differences are small, perhaps factors of 2 or 3, certainly less than a factor of 10.

Tolerance: Using hand tools and unaided eyes (or simple lenses), skilled human workers such as seamstresses, jewelers, and watchmakers can work to tolerances up to about 10^{-3} inches (or, perhaps, to 10^{-3} cm). Using mechanical and optical aids such as micrometers and microscopes, tolerances of 10^{-4} cm can be achieved by human workers such as engravers. Machine tools or automatic dimensional measuring devices with 1 to 3 degrees of freedom can be adjusted to move repetitively along paths or to points in space with comparable precision. However, robots with more degrees of freedom tend to be about a factor of ten less exact in repeating a motion than the most precise machine tools.

Power: Adult men in excellent physical condition can sustain a power output of 250 watts or more in short bursts, and 75 to 100 watts for fairly long periods. (A world class athlete such as a swimmer or bicyclist may be able to generate 300 or more watts of power output for several hours.) Machines, on the other hand, can be designed to deliver almost any amount of power. In practice, modern machine tools range in continuous effective power from one to one hundred kilowatts or more, depending on the application. Machines can outperform human workers in this regard by at least a factor of 10^2 or 10^3.

The cost-independent man/machine performance P ratios for the three groups of tasks, shown in Table 4, take the above comparisons into account. In short, human workers and machines are roughly in the competitive performance range for tasks in group I; humans are actually better at some tasks in group II because of their inherent advantage in sensory data processing and coordination. But machines have a very large intrinsic performance edge in group II (tool wielding). This explains why it pays a manufacturer to purchase and keep machine tools even for metalworking operations that are performed relatively infrequently, and why machine tool utilization, in terms of the ratio of actual metal-cutting time to machine availability time, is often so low in practice.[3]

Table 4: Man/Machine Performance Ratios for Generic Factory Tasks

Tasks Category	Measure	Man/Machine Ratio (P)
I parts transfer machine unloading	rate	$10^{-1} < P < 1$
II parts recognition and selection; machine loading; parts mating; inspection	rate/tolerance	$10^{-1} < P < 10$
III tool wielding	power/tolerance	$10^{-4} < P < 10^{-2}$

5 Human Controller Versus Sensor-Based Computer-Controller

We can now take it for granted that the existing function of direct labor in a factory is, essentially, that of control. The conventional control system for a manufacturing process based on information gathered by human eyes and ears, and processed by the human brain, can be represented as a simple model as shown in Figure 2a. The still primitive, computer-automated control system can be represented by a similar model, shown in Figure 2b.

In the past decade, much research has gone into the development of the elements of general purpose, computerized, sensor-based machine controllers. Significant progress has been made, to be sure. But it is now very clear, though perhaps only dimly understood a decade ago, that the most sophisticated, sensor-based computer control system that can be built today is still vastly inferior in input information processing terms to the human eye/ear/hand/brain combination. It is important to distinguish between raw input information, such as the optical signals received by the retina of the eye, and the output (control) information sent by the human brain to the hands or feet. The number of bits of output information is far smaller than the number of bits of input information. In fact, the ratio between input and output (the data reduction factor) is a useful performance measure for "smart" sensors.

The vision system of animals is comprised of an optical focussing device (lens), a light sensitive detector (retina), and a post-processing device (the visual cortex). The retina of a vertebrate contains about 10^6

[3] Actually, in low to mid volume manufacturing, it is authoritatively estimated that machine tools are engaged in productive cutting only 6% to 8% of theoretically available time (*American Machinist* (October 1980): 112).

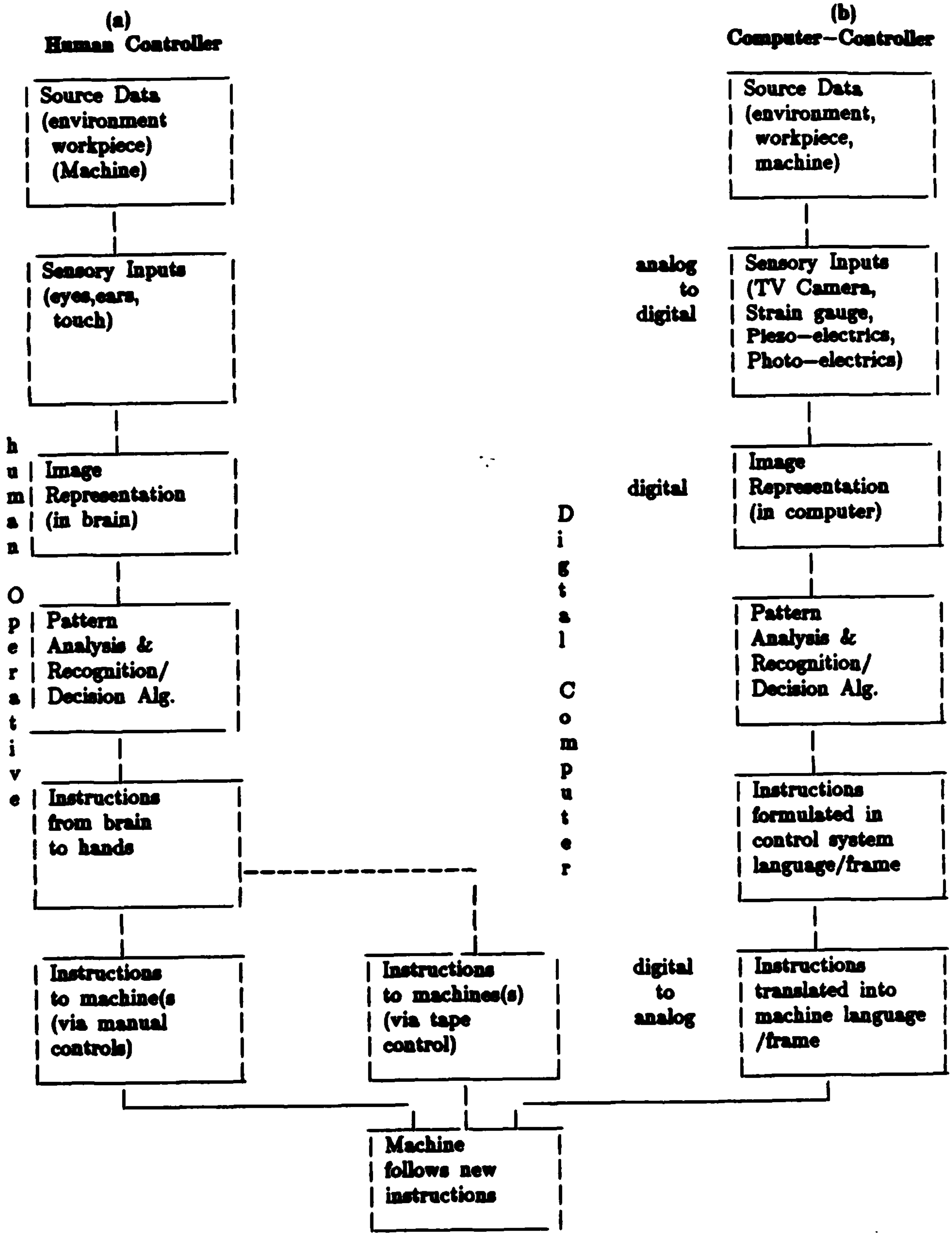

Figure 2: Human controller vs. sensor-based computer-controller

light-sensitive cells of two distinct types: cells that detect both light intensity and peak wavelength for daylight color vision (cones), and cells that detect only intensity light for night vision (rods). The retinas of animals, such as birds, that require very high quality daytime vision over wide angles cannot spare much retinal space for night vision and, conversely, animals that hunt at night cannot also enjoy good quality color vision by day.

Within the retina itself, the visual field is processed by about 2×10^7 neurons that reduce the input scene to a pattern of shapes delineated by "edges" that have curvature and motion. The retina sends a reduced or coded form of this visual input data via the optic nerve to the primary visual cortex at the back of the brain where about a billion neurons carry out further processing. Object classification recognition and interpretation, and motor responses are the responsibility of still other brain areas. The entire system processes about 10 "scenes" per second, where each scene consists of a matrix of about 1000 x 1000 picture cells (or pixels) in three primary colors. By comparison, a state-of-the-art minicomputer requires about two minutes to process one black and white scene recorded by a solid-state camera in the form of a matrix of 256 x 256 binary pixels.

In summary, the color picture recorded 10 times per second by the retina of a human eye initially contains about 50 times as much visual information as that recorded by a vidicon TV camera, or the equivalent, and it is processed 1000 times as fast for an overall performance ratio of the order of 50,000. While the above estimates are crude, they serve to make the key point. It seems clear that improved solid-state sensors and higher computational speeds and computer memory capacities alone will not quickly bring machine vision up to a level competitive with human vision. The gap is much too great. The problem is partially one of inappropriate computer architecture. Image representation and analysis are in principle more suited to parallel array processors than to von Neumann-type serial processors utilized by virtually all computers today. Very few parallel processing networks exist, as yet, and none are utilized in commercial vision/taction systems. Indeed, parallel processing computer architecture is still in its infancy. This will certainly change in the late 1980's, however, as the Japanese "5th generation computer project" undertakes a massive assault on developing specialized systems for the processing of visual data. It seems reasonable to suppose that U. S. firms will also move in this direction, if only to avoid being "scooped" by the Japanese. But parallel processors will only help with the first stage, viz., shape, edge and motion analysis. The higher order recognition and interpretive functions must await the development of suitable associative memory capabilities, plus algorithms and software capable of exploiting them.

By way of contrast to the computer-controlled machine, what are the relevant attributes of the human worker? He/she is born with high quality sensory equipment (eyes, ears, and hands), and develops excellent image representation and pattern analysis capabilities (brain), utilizing a parallel-processing architecture that is still very little understood. These capabilities are innate, even in children, and are not improved significantly by education or training. Inanimate sensors and computers are currently orders of magnitude inferior to the human brain in terms of information processing and interpretation. Even with another decade of research and development, the gap will still probably be enormous. Since human workers also need employment, why consider the use of sensor-based computerized control systems at all?

A clue to the answer to this question can be inferred from the example of a manned spaceship re-entering the atmosphere. In view of the foregoing comments, it would appear that the human pilot is actually capable of processing and integrating far more sensory information in real time than all of NASA's ground control computers combined. Why not let the human pilot handle the ship during re-entry? There is a good reason.

Consider the channels by which the pilot must get his information about the state of the ship. Either he must (like an aircraft pilot) read a set of dials or digital displays which involves successively moving and focussing his eyes many times, or he must acquire the information from a single integrated display prepared by the computer. Because the pilot has no direct nerve links to the spaceship's non-visual sensors, he cannot "see" the state of the ship holistically. The rate at which the pilot can acquire relevant information through his available channels is severely limited by the nature of the spaceship's sensory system. The immense information processing capabilities of his brain are, in fact, grossly underutilized. Meanwhile, the state of the ship changes very fast during re-entry. As it turns out, for certain very specialized and critical tasks such as maintaining the proper "angle of attack", the computer, with direct access to radar signals and other sensors in the ship, can calculate the necessary adjustments and send appropriate instructions to the controls much faster than it can present this data in visual form to the pilot. Thus, although the human eye/hand/brain combination can handle an enormous amount of relevant information in appropriate circumstances, i.e., playing a game of ping-pong, there are many situations where much of the *available* sensory information is more appropriate for computer-processing than for processing by the human brain.

This caveat obviously applies to the competition between human machine controllers and sense-based computer controllers for factory operations. The human brain can only process information that is channelled to it via eyes, ears, or sense of touch. He can deal with other kinds of information only if it is first translated into one of these forms. But the translation itself is a kind of information processing which typically requires a computer microprocessor. Hence, there are cases where it can be much more efficient to bypass the human altogether and let the computer process the data, make the decision, and issue instructions. In fact, this is already true for some factory operations, at least.

To make this argument clearer, consider the kinds of information relevant to controlling a machine tool. These are basically as follows:

- Workpiece position in tool coordinate systems
- Tool position in tool coordinate system
- Tool rotational speed, in tool coordinate system
- Resistance
- Tool wear rate

Instruments mounted on the machine can directly monitor such variables as

- Voltage drop (with respect to line voltage),
- Amperage, drawn by the motor,
- Torque or force feedback encountered by the tool,
- Rpm of the spindle,
- Vibration level at selected points in the tool/workpiece,
- Temperature at selected points in the tool/workpiece,
- Ultrasonic reflections from the workpiece,
- Optical reflections from the workpiece, etc.

From these data, fairly good inferences can be made by a computer about all of the relevant control variables. The machine operator, clearly, could monitor these same data visually via dials or displays. (He/she can also rely on supplementary information, such as the sound of the cutting tool or the smell of the hot oil.) But he *cannot* really utilize his inherently superior information processing capability because he cannot get *relevant* visual or tactile information any faster than the microprocessor-controller can. On the other hand, the computer can perform straightforward calculations and issue new instructions to the machine tool much faster and more accurately than the human could. For this reason, computer control (CNC) for a stand-alone machine tool or a "cell" of such tools is already demonstrably cost-effective as compared to human control.

The next question is the critical one: In what generalized circumstances can we predict sense-based computer-control will soon supplant human control of manufacturing processes? The answers will depend on two factors:

1. the cost and technical effectiveness of sensor-based computer control systems for specified functions, and

2. the cost-effectiveness of humans performing the same functions.

The second criterion is subtler than it first appears. Cost effectiveness for humans depends strongly on whether the information that is relevant to the control problem is directly available to the human worker in appropriate visual or tactile form, or whether it must be presented to the human in translated form on a dial or display. An example of the first case would be a truck driver maneuvering in traffic. For such a control task, the available information is relevant and one can immediately conclude that the sensor-based computer controller will not (soon) be competitive. In the second case, however, exemplified by the re-entering spacecraft or the machine tool already noted, the more specialized computer-controller will probably take over. This is particularly evident where a computer would be required to translate the basic data on the state of the system into a form that can be assimilated by a human observer.

To evaluate the potential applicability of a sensor-based computer controller to a given task in a manufacturing environment, it is necessary to characterize the essential control problem and the sources of relevant information.

As noted elsewhere, robots can already be used in place of humans for machine control and workpiece manipulation tasks that are sufficiently routine and repeatable such that internal feedback control, based on signals generated by the machiner itself, is adequate. On the other hand, human workers are still not being effectively challenged by robots, i.e., automation, for tasks inherently requiring high quality external visual or tactile data. Examples include inspection, parts handling, and assembly.

For the vast majority of machine operations, the essential items of control information are

1. the identification of workpiece (e.g., in a bin or from a conveyor belt),
2. the position/orientation of the workpiece in relationship to the machine,
3. the workpiece is loaded properly,
4. the machine is working properly,
5. the operation is complete, and
6. the part is "good" (i.e., inspection is satisfactory).

It is easy to see that items 1 and 2 are inherently visual, and therefore appropriate for human workers. On the other hand, other non-visual sensors can also provide this information in certain situations. Item 3 is usually based on force feedback, i.e., resistance. Information about the operation of the machine, item 4, must either be translated into visual form (dials, readouts) or the operator makes a judgment based on generalized visual (and audio) information. As already noted, machine-level data must be translated into a form accessible to the senses of the operator. Item 5 is derived from the state of the machine, e.g., motion stops. Item 6 is typically derived from visual appearance and "feel" (smoothness). Dimensional accuracy may be determined more precisely by a measuring device such as micrometer, a laser interferometer, etc. Here again, the worker gets his information from a display or readout.

There are still some inspection tasks where human eyes are better than any machine yet devised. Flaw detection in a complex shape or pattern, such as a computer chip, is still much easier for a human than any sense-based automatic system that can be built today. But with the number of circuit elements per chip already exceeding 250,000 in some cases, individual inspection by human eyes, even aided by microscopes, is no longer feasible. A faster and more reliable method of inspection is badly needed by the semiconductor industry, in particular.

Evidently, the problem of automating most machine operations depends largely on reducing the need for visual identification and manual orientation. The obvious strategy for accomplishing this is to "palletize" or "magazine" the workpieces so that they have a preprogrammed position and orientation as they enter the machine-cell. Another possibility is to design a specialized parts-feeder capable of orienting the parts. A compromise strategy is to use a similar mechanical device that merely separates the parts, e.g., on a belt, so that the vision system need only recognize its silhouette. Any of these methods reduces or eliminates the need for control information of the first two types noted above. The other types of control information are readily provided by simple sensors except, of course, the last (silhouette recognition) which requires vision.

The more difficult control problems arise in assembly. Here the sequence of motions can be very complicated. The types of control information required are

1. identification of the next workpiece,

2. position/orientation (P/O) of the workpiece in relation to the assembly,

3. insertion is proceeding properly,

4. part is properly inserted,

5. assembly is complete, and

6. assembly is "good."

The first two types of information are primarily visual, as previously, but the third and fourth are primarily tactile. As in the case of machining cells, the need for identification and position/orientation (P/O) information can be reduced, if not eliminated, by prepalletizing or magazining of parts. But fine-scale positioning of a part prior to insertio, especially where the fit is tight, involves both visual and tactile feedback. The only way to reduce the need for such feedback in a mechanical assembly system would be to sharply increase its precision, i.e., decrease the range of P/O variability in its moving parts. In any case, the P/O and insertion tasks in assembly operations appear to utilize visual/tactile information of the type humans can acquire and process very efficiently, while machines as yet cannot. In summary, machines can already outperform humans, by reasonable standards of comparison, in tasks that do not require vision or tactile feedback. For tasks in the latter category, however, humans and machines are both in the competition.

Relative performance depends, essentially, on how much sensory data needs to be processed and how it is acquired.

6 Restatement of the Problem

Referring again to Table 3 and the discussion leading up to it, it is evident that those factory tasks where human workers can still compete effectively with machines are all characterized by compromises between operating speed and precision. In fact, one can focus attention hereafter exclusively on tasks in category II. It is evident, moreover, that for tasks in this category, the limits on performance are attributable to limited information processing rates. This must be true for either human workers or machines. A further implication seems inescapable: since human workers are able to compete effectively with the superior inherent speed and reliability of machines only by virtue of superior vision and taction, it follows that the more a human's performance is degraded by interference with these senses, the more inherently sense-dependent the task is and the greater the advantage humans have over machines in performing that particular task. To put it another way, one may ask again: is there an objective measure by which the inherent abilities of machines and human workers can be compared, for purposes of determining, in principle, which jobs are likely to be vulnerable to competition by machines during the next two decades? One can conclude that the relative degradation in performance due to sensory deprivation is exactly the desired measure for comparison.

All that remains, then, is to define a set of representative tasks that would fit into category II, measure performance under a controlled set of conditions, including various degrees of sensory deprivation, and check the results for internal consistency. It is important to bear in mind that some tasks are likely to be more dependent on vision than on taction, and conversely. Moreover, it will be seen that there is some interaction between the two senses, resulting in the possibility of anomalous behavior.

To test this concept, a set of experiments was proposed by the author and carried out under his direction. For purposes of the experiment, we defined a number of representative assembly tasks, viz., assembly of a pencil sharpener, tinkertoy, flashlight, nuts and bolts, and insertion of wires and "chips" into a printed circuit (PC) board. We then carried out extensive performance time measurements under various conditions. A complete description of the experiments and the results are included in a separate report [Miller 1984]. Only summary results are, therefore, given here.

As a matter of possible interest, one notes that the average time taken for each of the assembly tasks for workers with no sensory impairment, using both hands, was as listed in Figure 3 (in order of increasing difficulty). An "index of difficulty" could be computed for each experiment, using equation (1) given earlier. The index would be essentially proportional to the time required.

Task	Time (sec.)
nuts and bolts	5.6
pencil sharpener	9.8
flashlight	14.0
wire and chip	20.0
tinkertoy	29.0

Figure 3: Average time of assembly tasks for workers with no sensory impairment and using both hands

The next step was to carry out similar measurements for workers with impaired senses. The first case is characterized by impaired vision but unimpaired taction results (Table 5).

Table 5: Relative Performance Degradation with Impaired Vision

Rank 1 = least dependent on sensory feedback
Rank 2 = most dependent on sensory feedback

	Fractional Decrease in Assembly Rate (units/hr)		
Sensory Dependence Ranking Assembly	Gause Bandage (GB)	Wax paper Bandage (WB)	No Sight (NS)
1. Nuts and bolts	0.097	0.200	0.200
2. Flashlight	0.091	0.380	0.508
3. Pencil sharpener	0.170	0.500	0.670
4. Tinkertoy	0.383	0.588	0.670
5. Wire and chip	1.000	1.000	1.000

Note that the wire and chip experiment could not be done without sight. The most notable thing about the results in Table 5 is their internal consistency: for minor visual impairment (gauze bandage) the rank order is exactly the same as it is for more extreme levels of impairment. The next case (Table 6) compares performances with impaired taction.

There are three anomalies in Table 6, denoted by asterisks(*). It was anomalously difficult to assemble the flashlight with heavy gloves. It was anomalously difficult to assemble a pencil sharpener with wooden splints. On the other hand, the wire and chip insertion was anomalously easier with splints than with heavy gloves.

In the case of the flashlight, video recordings indicate clearly that there was a special problem in inserting the glass correctly in the lens cap with heavy gloves because of their sheer bulk. Similarly, the bulky gloves made it difficult to grasp the small electronic components. In the case of the pencil sharpener, it proved very

Table 6: Relative Performance Degradation with Impaired Taction

Rank 1 = least dependent on sensory feedback
Rank 5 = most dependent on sensory feedback

Sensory Dependence Ranking Assembly	Fractional Decrease in Assembly Rate (units/hr) Light Gloves (LG)	Heavy Gloves (HG)	Wooden Splint "Gloves" (WG)
1. Flashlight	.0277	.508*	.583
2. Pencil sharpener	.075	.395	.775*
3. Tinkertoy	.0823	.420	.623
4. Nuts and bolts	.097	.429	.781
5. Wire and chip	.130	.672	.583*

difficult to grip and engage the heavy and awkward handle on the threaded shaft with wooden splints on the fingers. In all three cases, the problem (clearly evident on videotapes) was due to difficulties peculiar to the nature of the gripping surface and the shape or size of the part in question. The best rank order is, therefore, determined by the results obtained with light gloves (column 1).

Table 7: Relative Performance Degradation with Jointly Impaired Vision and Taction

Rank 1 = least dependent on sensory feedback
Rank 5 = most dependent on sensory feedback

Sensory Dependence Ranking Assembly	Fractional Decrease in Assembly Rate (units/hr) (GB/LG)	(WB/HG)	(NS/WG)
1. Flashlight	0.114	0.642	0.910
2. Nuts and bolts	0.177	0.588	0.943
3. Pencil sharpener	0.246	0.778	0.950
4. Tinkertoy	0.431	0.788	0.915
5. Wire and chip	1.000	1.000	1.000

These results are internally consistent, except for the tinkertoy assembly which seems to have been anomalously easy in the case of no sight and "wooden gloves" (NS/WG). This is probably a purely statistical anomaly since the data variances for the third column are very large. The ranking given by the first two columns are identical.

Further analysis of Tables 5 through 7 reveals an interesting and surprising fact: *for all three cases, the sensory-dependence rank-ordering of four of the five assemblies was the same, regardless of which senses were impaired,* viz.,

- flashlight
- pencil sharpener
- tinkertoy
- wire and chip

However, the relative ranking of the "nuts and bolts" assembly shifted dramatically from number 1 (least degraded) for vision impairment alone to number 4 for tactile impairment alone, and number 2 (intermediate) for the case of joint impairment of both senses. This is clear empirical evidence that the act of engaging a threaded nut on a bolt is much more dependent on taction than on vision, whereas for most tasks, vision and taction are apparently to some extent mutually substitutable.

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